



Next Generation, High-Efficiency Boosted Engine Development

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DE-EE0008878

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11:45 a.m. EDT
45-Minutes

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Project Overview

Partners

Ford Motor Company
FEV North America Inc.
Oak Ridge National Lab (ORNL)



Barriers

- Engine efficiency can be improved by increasing the compression ratio (CR). CR is limited by autoignition (knock), heat losses, and unfavorable combustion chamber shapes.
- Dilute stoichiometric combustion offers benefits in engine efficiency but is limited by combustion stability and exhaust gas recirculation (EGR) flow capacity.
- Engine friction, pumping work, and accessory loads must be minimized to improve net efficiency.
- Reducing vehicle mass improves fuel economy but is limited by structural requirements and manufacturing techniques.

Timeline

Project start:	4Q 2019
Project end:	4Q 2022
Percent complete:	75%

Budget

Total project funding: \$10M

- | | | | |
|--------------|-------------|--------------------|-------------|
| • DOE share: | \$7,566,731 | • Budget period 1: | \$3,897,279 |
| • EERE: | \$7,416,731 | • Budget period 2: | \$4,641,989 |
| • FFRDC: | \$150,000 | • Budget period 3: | \$1,311,630 |
| • Recipient: | \$2,434,167 | | |

Any proposed future work is subject to change based on funding levels.

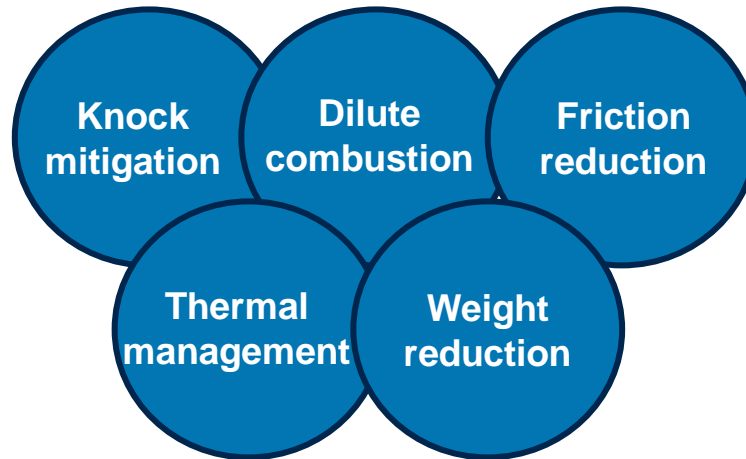


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Project Relevance and Goals

Objective: Design, evaluate, build and test an engine that will achieve 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150 baseline.

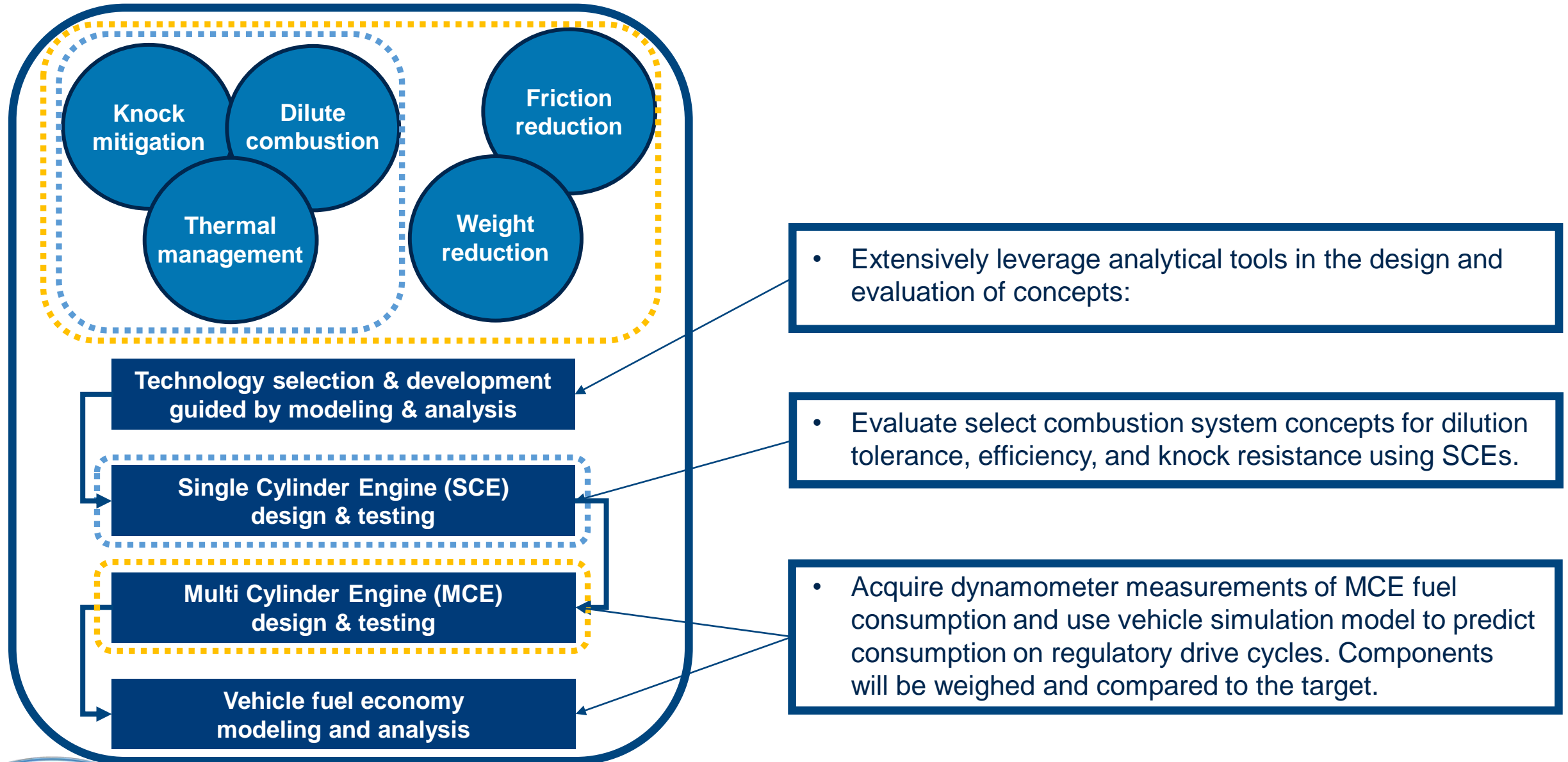
Impact: Technologies investigated in this project will reduce CO2 emissions of the highest production volume powertrains found in light duty vehicles by addressing the following barriers:



Supports the Vehicle Technologies Office (VTO) Advanced Combustion Engines (ACE) Subprogram goals of improving light-duty engine efficiency, reducing mass and hence improving passenger vehicle fuel economy.



Project Approach - Workstreams



Project Approach – Technical content*

Weight reduction	Knock mitigation	Dilute combustion	Friction reduction	Thermal management
Weight reduction	Knock mitigation	Dilute combustion	Friction reduction	Reduced heat losses
Composite structural oil pan	Miller cycle (reduced effective CR)	High tumble	High porosity mirror finish PTWA	High EGR rates
Composite front cover	Fast burn rate (Pre-chamber ignition)	High energy ignition (Multi-plug, pre-chamber)	Form hone professional	Temperature swing coating
Composite engine mounts	Bore/Stroke optimization	Bore/Stroke optimization	Offset crankshaft	Bore/Stroke optimization
Printed cylinder head / block cores	Intake port insulation / cooling	High flow EGR system	Roller bearing (#1 main and cam journal)	Split cooling / advanced cooling strategy
High porosity mirror finish PTWA	Integrated liquid cooled charge air cooler	Advanced boost system	Variable displacement oil pump	Electric water pump
Architecture change (Inline 6 in lieu of V6)	Targeted piston cooling		0W16 viscosity oil	
Integrated Exhaust Manifold	Electric water pump		Split cooling / advanced cooling strategy	
Single bank after treatment	Split cooling / advanced cooling strategy		Electric water pump	

Every engine system redesigned inline with project objectives



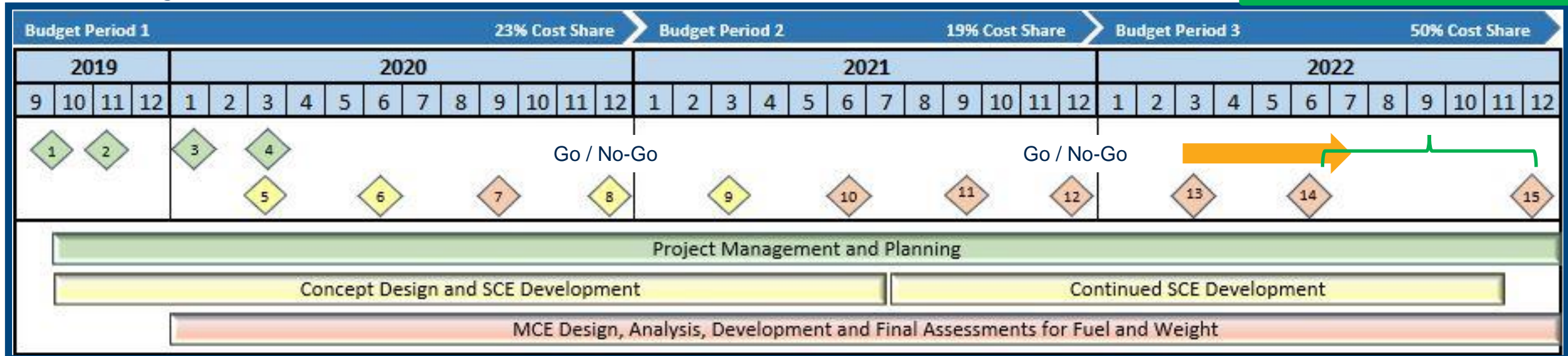
*Partial list of the technologies being evaluated

PTWA = Plasma transfer wire arc (spray bore)
CR = Compression ratio

Project Milestones

Hardware delays pushed build [Milestone #13] out ~4 months

Goal = deliver final assessment
[Milestone #15] on time with Q3 /
Q4 recovery, but plan has risk



#	Date	Event / Milestone	%
1	10/01/19	Conditional award effective	100
2	11/13/19	DOE on-site kick-off	100
3	01/27/20	Definitized DOE award executed	100
4	03/16/20	FEV sub-contract executed, purchase order issued	100
5	03/31/20	SCE assumptions, targets & hard points defined	100
6	06/30/20	SCE hardware frozen, 3-plug and pre-chamber	100
7	09/30/20	Composite oil pan concept selected	100
8	12/31/20	Analytical assessment of combustion metrics	100

#	Date	Event / Milestone	%
9	03/31/21	SCE development complete & MCE ignition selected	100
10	06/30/21	MCE design frozen	100
11	09/30/21	MCE hardware procurement	95
12	12/31/21	Analytical assessment of SCE & MCE design vs. targets	100
13	03/31/22	MCE built, install and debug complete	5
14	06/30/22	Initial fuel consumption map complete	0
15	12/31/22	Final assessment of vehicle fuel economy & engine weight	10

Hardware delays, shutdowns & facility access limitations due to COVID have impacted SCE development and block fabrication.



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SCE = Single cylinder engine 6
MCE = Multi cylinder engine

Accomplishments & Progress –SCE Combustion Development

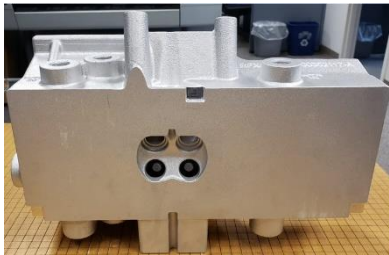
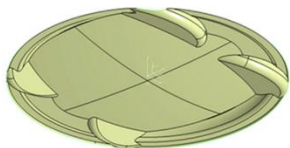
Dilute combustion Knock mitigation

SCE Common Elements

Cylinder bore diameter:	84 mm	Main chamber fuel:	Port fuel injection (PFI) and side direct injection (DI)
Stroke:	112 mm	Exhaust event duration & timing:	245°, Closing 25° after top dead center
Compression ratio (CR):	14.0:1	Intake event duration / timing:	Hydraulic continuously variable valve lift

3-Plug SCE

- Three spark plugs along the axis of the crank
- Charge motion via tumble intake port with valve masking
- Engine installed in cell, available for further testing



Active Pre-Chamber SCE

- Pre-chamber with spark plug, air and fuel injectors
- Charge motion via tumble intake port, no valve masking
- Engine installed in cell, further testing in process



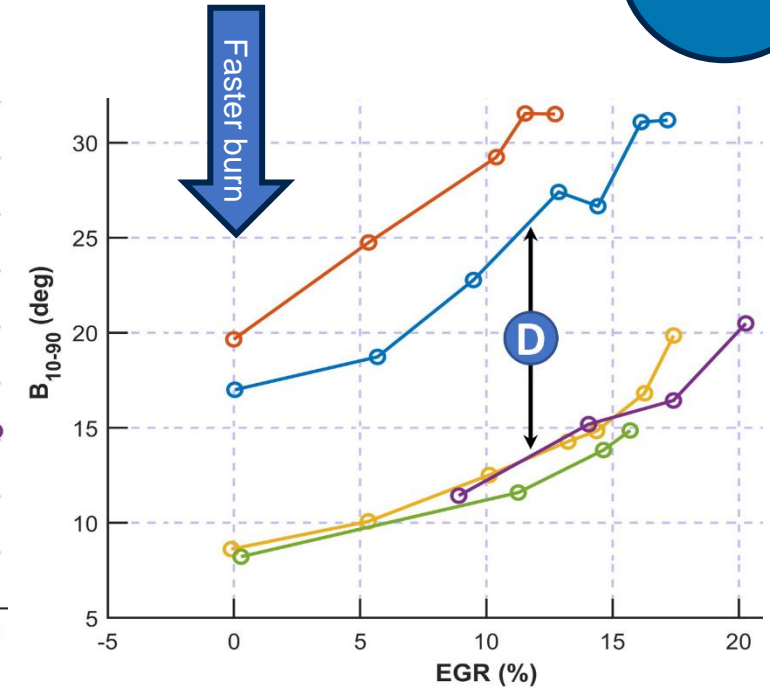
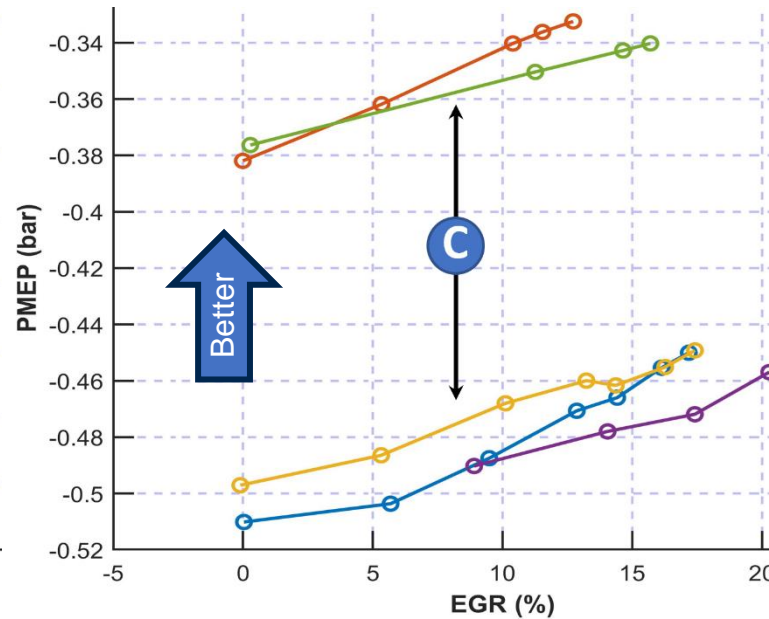
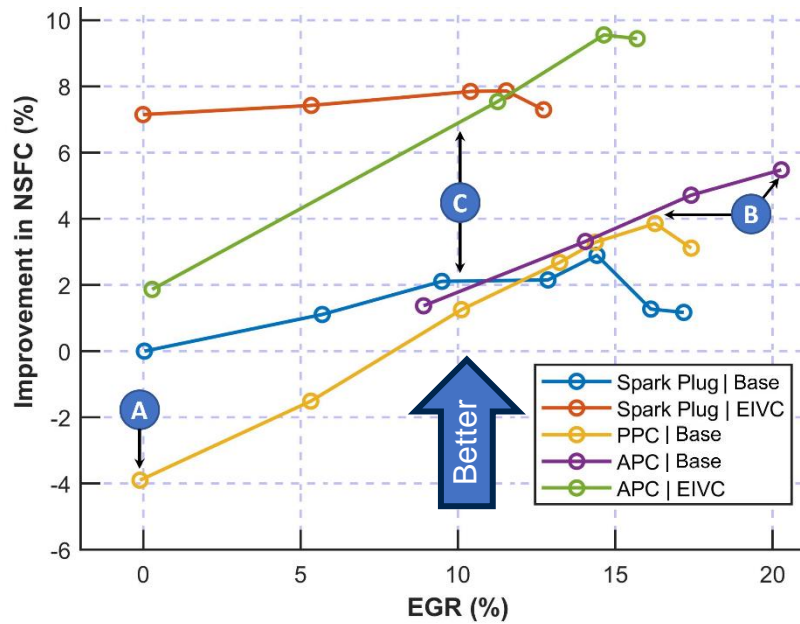
SCE testing used to validate combustion system design



Accomplishments & Progress – Pre-Chamber SCE Test Results

1500 rpm 3.2 bar NMEP

Dilute
combustion



- A. Heat Transfer:** PPC at 0% EGR results in 4% worse NSFC when compared to a spark plug ignition system
- B. Dilution:** PPC and APC increased dilution tolerance and improved NSFC when using a base fixed duration intake strategy

- C. Pumping Work:** EIVC minimizes PMEP resulting in significant NSFC improvements
- D. Burn Rates:** The main combustion chamber B_{10-90} durations are significantly improved with PPC and APC

Effects of valvetrain and ignition technology quantified



EGR = Exhaust gas recirculation
LIVC = Late intake valve closing
EIVC = Early intake valve closing

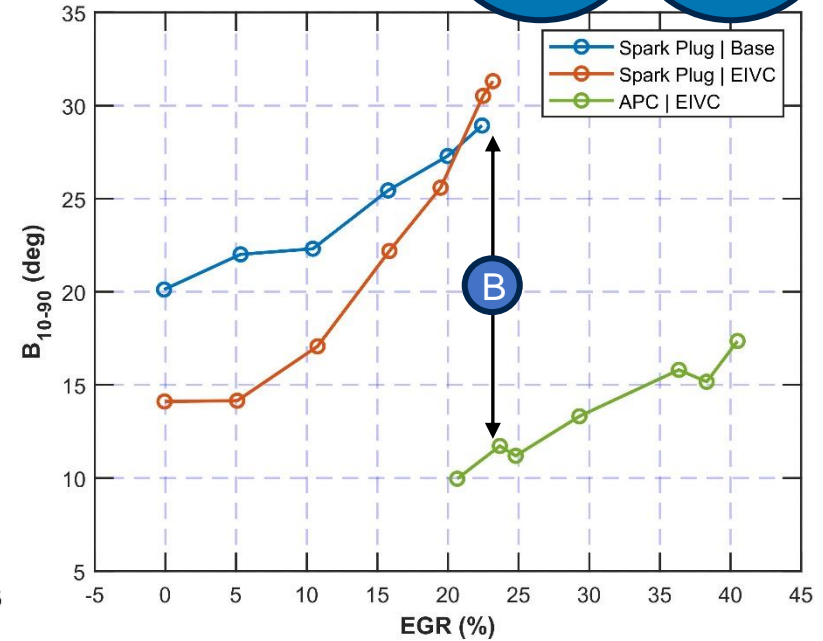
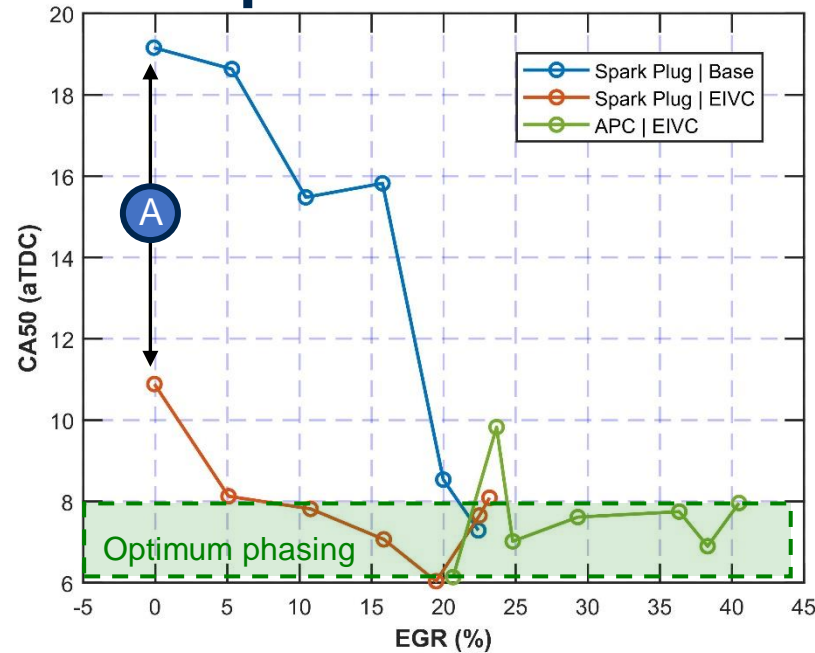
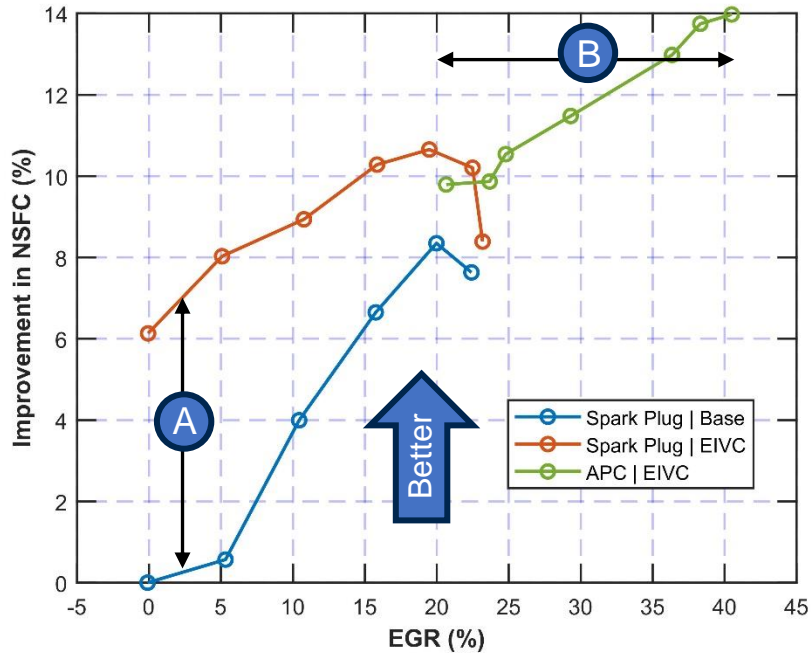
PPC = Passive pre-chamber
APC = Active pre-chamber (fuel and air)
NSFC = Net specific fuel consumption

B_{10-90} = Crank angle burn duration from 10% to 90% mass fraction burned
PMEP = Pumping mean effective pressure
NMEP = Net mean effective pressure

Accomplishments & Progress – Pre-Chamber SCE Test Results

1500 rpm 5.6 bar NMEP

Dilute combustion Knock mitigation



- A. Knock mitigation:** EIVC reduces effective compression ratio and reduces the tendency for knock improving NSFC
- B. Dilution tolerance:** Active pre-chamber ignition enhances burn rate and improves EGR tolerance

Verified pre-chamber functionality and stability to 40% stoichiometric EGR



EGR = Exhaust gas recirculation
LIVC = Late intake valve closing
EIVC = Early intake valve closing

PPC = Passive pre-chamber
APC = Active pre-chamber (fuel and air)
NSFC = Net specific fuel consumption

B₁₀₋₉₀ = Crank angle burn duration from 10% to 90% mass fraction burned
CA50 = Crank angle at which 50% of the mass has burned
NMEP = Net mean effective pressure

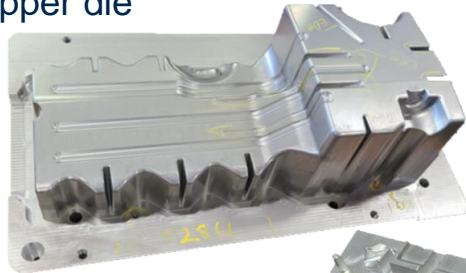
Accomplishments & Progress – Material Weight Reduction

Weight
reduction

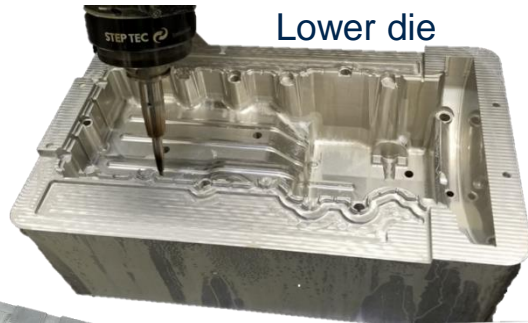
Composite Structural Oil Pan

- Collaborating with Oak Ridge National Lab to design, develop, manufacture and test oil pans as a demonstration component
- 43% mass reduction relative to an aluminum oil pan
- Compression molded glass / carbon fiber hybrid material selected (Solvay Amodel® PXM-18179)

Upper die



Lower die



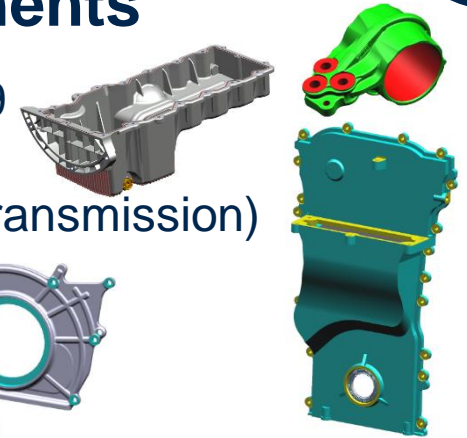
Bell housing insert



Components

Solvay Amodel® PXM-18179

- Oil pan
- Mounts (left engine and transmission)
- Front cover
- Rear seal retainer



Sabir Ultem™ 1010

- Windage tray
- EGR mixer



Magnesium

- Cam cover



Composites and other light-weight materials incorporated into engine component designs when possible

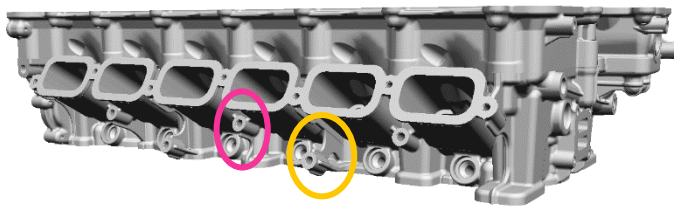
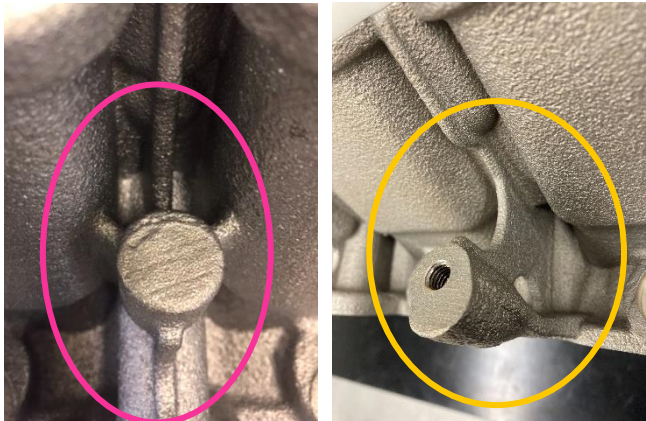


Accomplishments & Progress – Design / Manufacturing Weight Reduction

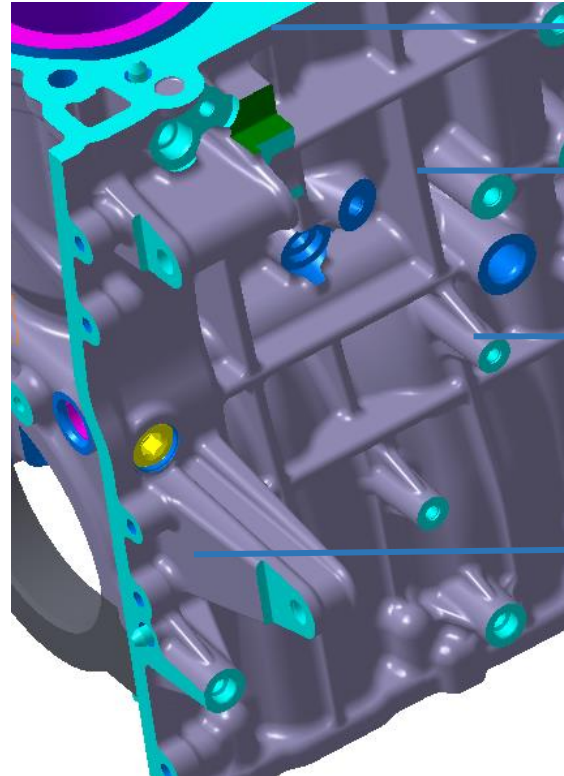
Weight
reduction

- Additive cores demonstrated on head and evaluated on block.

Demo head features



Die cast design



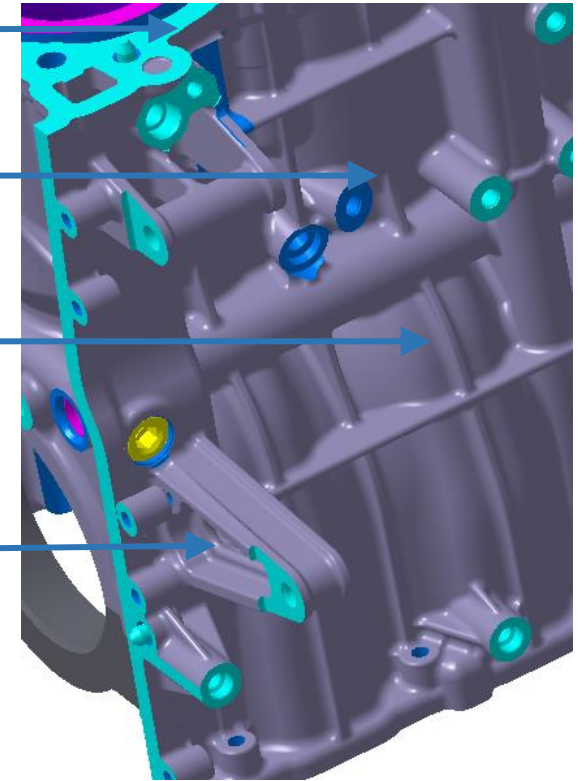
Contoured deck face to
match head

Reduced draft
and ribbing

Removed bosses for
deleted components

Cored out
excess mass

Additive core design

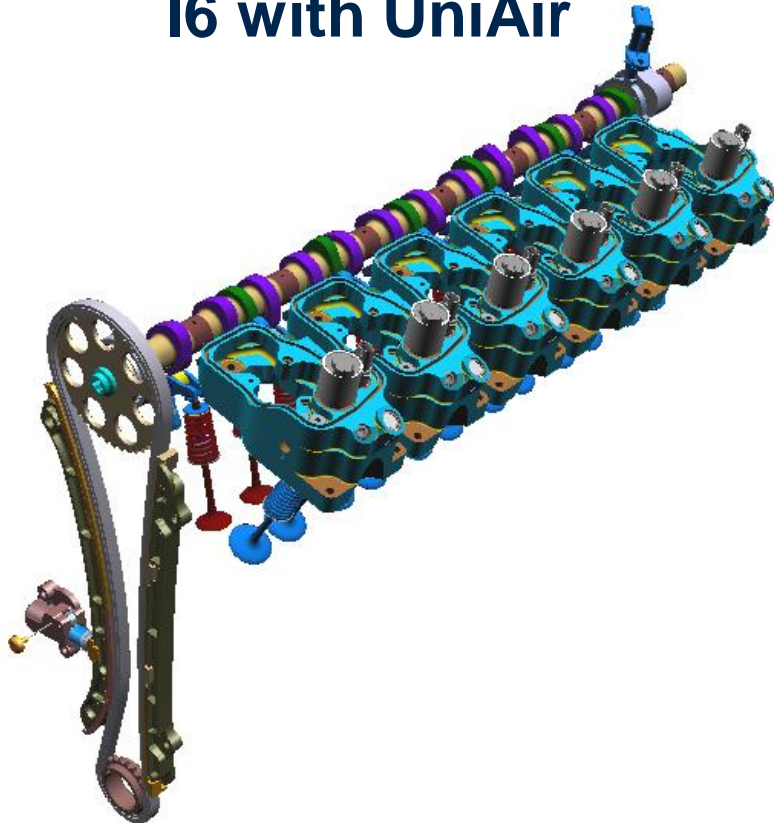


~2.2% Engine weight benefit from the block design

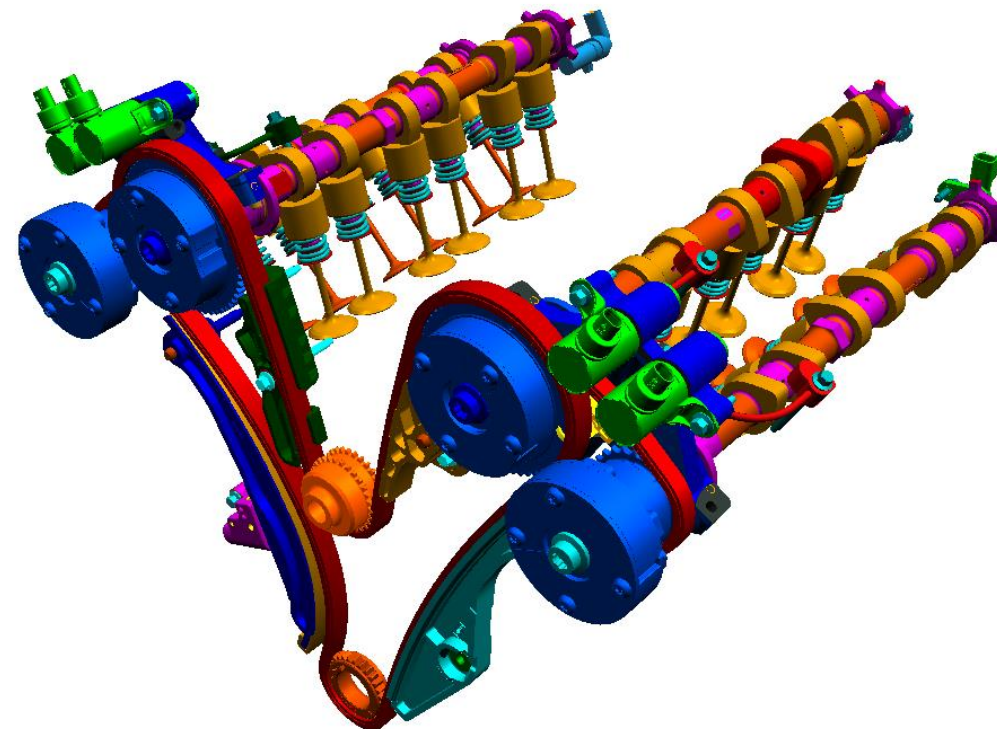
Accomplishments & Progress – Architecture / Technology

Weight
reduction

I6 with UniAir



Baseline V6



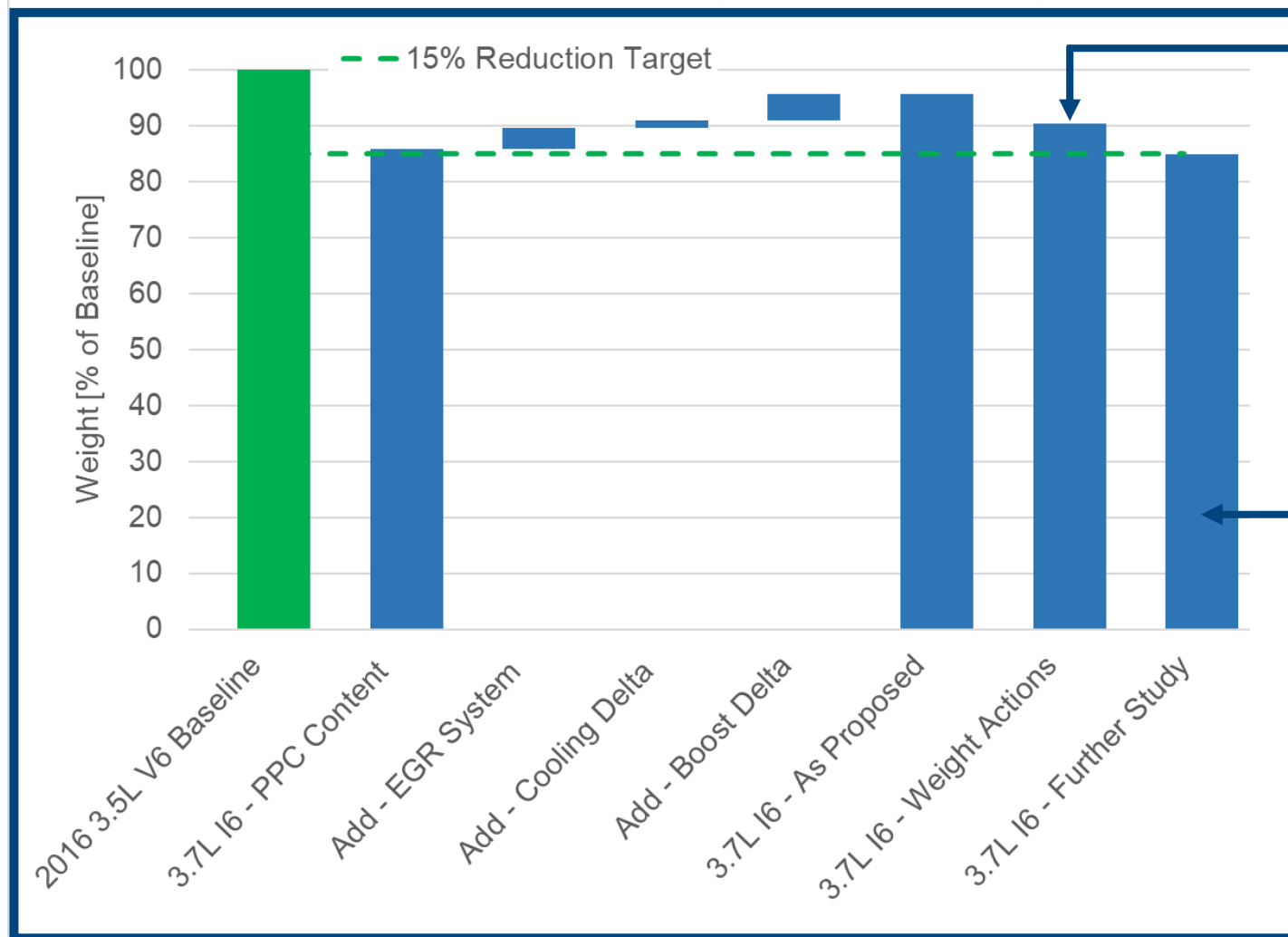
~1.5% Engine weight benefit



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Accomplishments & Progress – Weight Status

Weight
reduction



Identified **Weight Actions** with no impact on attributes:

- Reduced weight crankshaft
- Composite intake manifold
- Magnesium cam cover & other components
- Catalyst canister inlet / downpipe optimization
- Other component optimizations

Additional weight actions requiring **Further Study**. May impact attributes:

- Further component weight reduction
- Single twin-scroll turbo
- EGR cooler / throttle delete
- Reduced max engine speed
- Reduced stroke

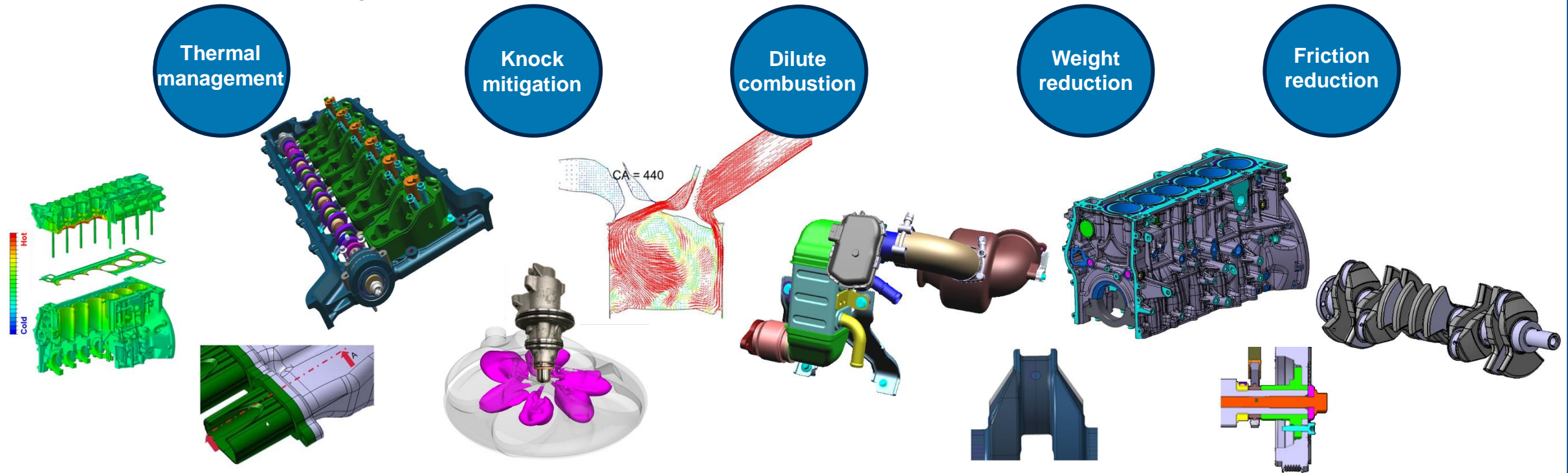
**Actions identified to achieve 10% weight reduction.
Additional items being studied to achieve 15% target.**



Accomplishments and Progress – MCE Development

2021

- There has been a Major focus this period on MCE component design supporting the fuel economy and weight targets
- Over 1,300 parts required for each dynamometer engine build
- Numerous Ford first and industry leading technologies incorporated into the design necessary to achieve 23% fuel economy improvement and 15% weight reduction



MCE design nearly completed. Part orders are being placed.



Accomplishments and Progress – MCE Fabrication

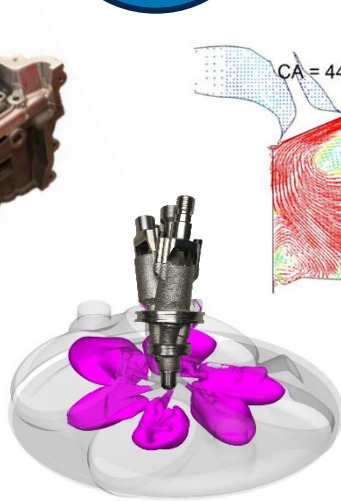
2022

- There has been a Major focus this period on MCE component fabrication
- Over 1,300 parts required for each dynamometer engine build
- Numerous Ford first and industry leading technologies incorporated into the design necessary to achieve 23% fuel economy improvement and 15% weight reduction

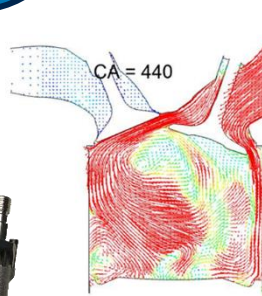
Thermal
management



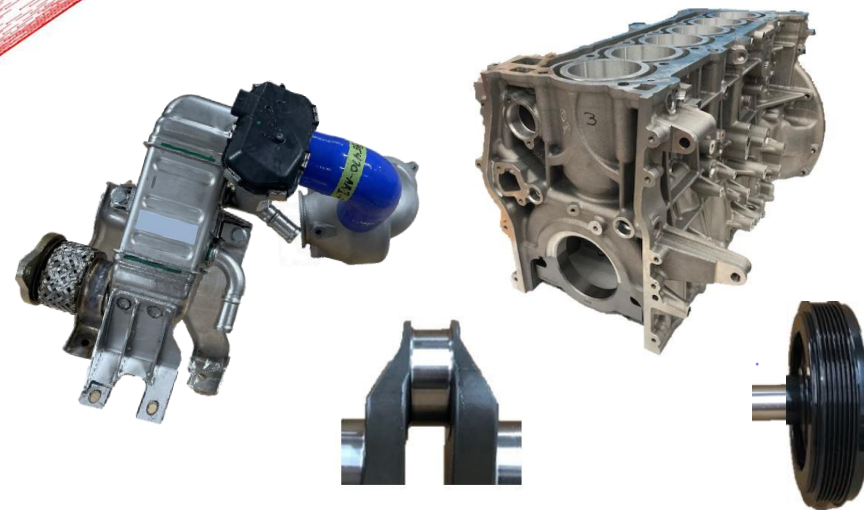
Knock
mitigation



Dilute
combustion



Weight
reduction



Friction
reduction



Completed MCE hardware fabrication. Engine build in process.



Response to Previous Year Reviewers' Comments

- *The project goals are well clarified. But the focus is much more evident in the combustion work than the weight reduction work. It is not clear that the weight reduction effort is as central as it seemed that the project was intended for.*
- *'One of the big concerns is the weight reduction. Currently, it may face challenging if the weight gain from EGR and cooling system would be added into the total weight reduction goal.'*
 - *Response: Going from a V6 to an I6, improved manufacturing techniques, and lightweight materials all provide weight saving opportunities but trade-offs to the weight have been made to push the engine efficiency and develop engine technologies that are not currently used in high-volume production applications. It may be possible to meet the fuel economy targets without some of the added technologies. A reduced set will be considered for meeting both the efficiency and weight targets.*
- *There is a pathway to improved engine fuel consumption with the engine technology packages being considered. Please clarify whether the fuel economy target is CAFE (unweighted FTP-75 and HFET only) or sticker (2 or 5 cycles, but weighted to predict the fuel economy seen by drivers).*
 - *Response: The fuel economy improvements are based on the calculation used for corporate average fuel economy (CAFE):*
$$1/\text{MH_mpg} = 0.55/\text{City_mpg} + 0.45/\text{Hwy_mpg}$$

MPG = Miles per gallon
CAFE = Corporate average fuel economy
MH = Metro highway
HWY = Highway

Any proposed future work is subject to change based on funding levels.



Collaboration and Coordination with Other Institutions



Industry Subrecipient Project Partner

- Co-design / co-development of pre-chamber
- Intake air system design / development
- EGR system design / development
- Piston design / development
- Lubrication system design / development
- Design support for various components

More than 20 additional companies are engaged in developing prototype components greatly expanding the knowledge base leveraged to successfully complete the project.



DOE VTO National Laboratory Partner

- Co-design / development of composite structural oil pan
- Material selection, tool development, part production

Any proposed future work is subject to change based on funding levels



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Remaining Challenges and Barriers

- The technologies added to achieve the engine efficiency goals have increased the challenge of meeting the weight reduction target. Mitigating actions:
 - Pursuing light weighting beyond the items identified in the project proposal.
 - Exploring if a de-contented version of the engine can meet the fuel economy goal.
- Several issues have delayed manufacturing of the cylinder block including: COVID related manpower shortages, facility issues, and casting porosity. Mitigating actions:
 - Conducting a pre-build with a non-functional block to identify assembly issues and to assist in fabrication of the test stand and instrumentation.
 - Continuing SCE testing to supplement MCE testing.
- The technology included on the demonstration engine requires extensive prototype engine controls (using 3 PCMs). Additional debugging may be required.



Proposed Future Research

- **Budget Period 3 – MCE Development and Vehicle Simulation** **Jan. 2022 – Dec. 2022**
 - Complete MCE builds. Install and debug engines in the dynamometer test cells.
 - Conduct experimental fuel economy optimization at key operating points to provide emissions and fuel consumption data to support vehicle level fuel economy modeling.
 - Complete engine weight improvement assessment against the 15% target.
 - Complete vehicle fuel economy improvement assessment against the 23% target.



Summary

- **SCE testing indicates the combustion system meets the dilution tolerance targets.**
- **Major MCE hardware design and fabrication work is now complete. MCE assembly is in process.**
- **Additional weight reduction actions are being evaluated. A careful balance of fuel economy, performance, and weight will be required to achieve the targets.**





Technical Backup Slides

Estimated Fuel Economy Benefits From Project Proposal

Proposed Actions	Baseline	% FE Improvement	Comments
13:1–15:1 CR	10:1	6-8	Requires significant knock mitigation. Airpath thermal mgt., split and optimized cooling system, Miller valve events, lube system optimization for piston cooling, high conductivity valve seats and guides
35-50% Cooled EGR	0%	2-5	Requires advanced ignition (active pre-chamber, multi-plug or other unconventional ignition technologies) and boost system improvements
B/S opt: 0.72-0.82	1.06	1.0-2.0	Efficiency / CR enabler, likely requires architecture changes
CVVL	Ti-VCT	2.5-3.5	Enables Miller and transient fuel economy
Stop-Start	-	3.0-4.0	
Down speeding	6 speed	2.0-4.0	10 speed transmission in place of 8 speed
Temperature swing coatings	-	1-2	Reduced heat losses with less intake charge heating
Friction reduction	base	1-2	Form hone, high porosity PTWA with mirror finish, roller bearings, variable displacement oil pump, offset crank, advanced cooling strategy, split and optimized flow paths
Fast warm-up	base	0.2	Advanced cooling system
Weight reduction		1	Weight reduction achieved through architecture change, composite materials, and additive manufacturing largely offset by adding EGR system and upgrading the boost system
Engine upsizing	base	-1.7	Increased displacement to offset lower power density
Total		~23	

Any proposed future work is subject to change based on funding levels

CVVL = Continuously variable valve lift



Estimated Engine Weight Walk From Project Proposal

Proposed Actions	Original % Weight Reduction	Updated % Weight Reduction	Comments
Engine architecture	2.8	0.9	Shift from a "V" to an "I" engine architecture
Advanced materials	2.7	3.1	Carbon fiber compression-molded oil pan, composite carbon fiber compression-molded front cover, additive hollow titanium connecting rods, composite engine mounts, composite rear seal carrier, composite EGR mixer
Exhaust manifolds	3.6	2.7	Eliminate two cast steel manifolds and integrate into the cylinder head
Single bank aftertreatment	3.5	4.4	Reduced number of catalysts bricks, canisters, and sensors
Optimized cylinder head	1.2		Use indirect additive manufacturing to optimize head for weight, updated % weight reduction captured under engine architecture
CVVL	1.3	-0.1	Delete (2) intake cams, intake VCTs, and cam timing sensors and add UniAir
Optimized cylinder block	0.8	2.2	Use indirect additive manufacturing to optimize block for weight
PTWA	1.2	1.4	Replace (6) cast iron bore liners with plasma transfer wire arc (PTWA) coating
Battery optimization	3.4	3.3	Replace 12V flooded / wet cell lead acid with Li-ion 12V starter battery
EGR system	-3.3	-3.9	Baseline does not have an EGR system
Engine thermal actions	-1.8	-2.7	Addition of piston cooling jets, intake runner spacer, and advanced cooling system
Long stroke	-2.7	-5.8	Deck height increase up to 20 mm, additional crank structure to accommodate long stroke
Boost System	2.4	-1.3	A 2.4% weight reduction for a turbocharger delete or a single turbocharger boost system was captured in the original % weight reduction summary under engine architecture
Net Weight Savings	15.1	4.3	



Any proposed future work is subject to change based on funding levels

EGR = Exhaust gas recirculation

VCT = Variable cam timing

CVVL = Continuously variable valve lift